LIFE CYCLE IMPACT ASSESSMENT (LCIA)

A comparative life cycle assessment of two treatment technologies for the Grey Lanaset G textile dye: biodegradation by *Trametes versicolor* and granular activated carbon adsorption

Xavier Gabarrell · Mercè Font · Teresa Vicent · Gloria Caminal · Montserrat Sarrà · Paqui Blánquez

Abstract

Purpose The aim of this study is to use life cycle assessment (LCA) to compare the relative environmental performance of the treatment using *Trametes versicolor* with a common method such as activated carbon adsorption. This comparison will evaluate potential environmental impacts of the two processes. This work compiles life cycle inventory data for a biological process that may be useful for other emergent biotechnological processes in water and waste management. LCA was performed to evaluate the use of a new technology for the removal of a model metal-complex dye, Grey Lanaset G, from textile wastewater by means of the fungus *T. versicolor*. This biological treatment was compared with a conventional coal-based activated carbon adsorption treatment to determine which alternative is preferable from an environmental point of view.

Materials and methods The study is based on experimental research that has tested the novel process at the pilot scale. The analysis of the biological system ranges from the production of the electricity and ingredients required for the growth of the fungus and ends with the composting of the residual biomass from the process. The analysis of the activated carbon system includes the production of the adsorbent material and the electricity needed for the treatment and regeneration of the spent activated carbon. Seven indicators that measure the environmental performance of these technologies are included in the LCA. The indicators used are climate change, ozone depletion, human toxicity, photochemical oxidant formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, metal depletion and fossil depletion.

Results The results show that the energy use throughout the biological process, mainly for sterilisation and aeration, accounts for the major environmental impacts with the inoculum sterilisation being the most critical determinant. Nevertheless, the biological treatment has lower impacts than the physicochemical system in six of these indicators when steam is generated directly on site. A low-grade carbon source as an alternative to glucose might contribute to reduce the eutrophication impact of this process.

Conclusions The LCA shows that the biological treatment process using the fungus *T. versicolor* to remove Grey Lanaset G offers important environmental advantages in comparison with the traditional activated carbon adsorption method. This study also provides environmental data and an indication of the potential impacts of characteristic processes that may be of

X. Gabarrell (✉) · M. Font
Sostenipra, Institut de Ciència i Tecnologia Ambientals (ICTA),
Chemical Engineering Deparment,
Xarxa de Referència en Biotecnologia (XRB) de Catalunya,
Universitat Autònoma de Barcelona (UAB),
Escola d'enginyeria. Campus Bellaterra,
08193 Cerdanyola del Vallès, Catalunya, Spain
e-mail: xavier.gabarrell@uab.cat

T. Vicent · M. Sarrà · P. Blánquez
Departament d'Enginyeria Química,
Institut de Ciència i Tecnologia Ambiental, Escola d'Enginyeria,
Universitat Autònoma de Barcelona,
08193 Bellaterra, Spain

G. Caminal
Unitat de Biocatàlisis Aplicada asociada al IQAC (CSIC-UAB),
Escola d'Enginyeria, Universitat Autònoma de Barcelona,
08193 Bellaterra, Spain

interest for other applications in the field of biological waste treatment and wastewater treatment involving white-rot fungi.

1 Introduction

Metal-complex azo dyes are widely used in the textile finishing industry, especially the 1:2 (metal/dye) metal complexes due to their ability to produce photostable colours on polyamide and wool fibres. The most common metals forming part of the chromophore are chromium, cobalt and copper (Eippcb 2003; Poiger et al. 2000). Although the dyeing process can be optimised to achieve high exhaustion and fixation levels (Eippcb 2003), the unfixed dye, which may end up in the wastewater, must be treated given its high persistence and non-biodegradability.

The most widely used methods for textile dye treatment use physical and chemical means, such as membrane filtration, advanced oxidation and adsorption by activated carbon (Robinson et al. 2001). With regard to metal-complex dyes, activated carbon and membrane filtration are effective without delivering the metals to downstream processes (Eippcb 2003). Furthermore, laboratory and pilot tests of biological processes employing alternative microorganisms, such as white-rot fungi, have been shown to be very effective in degrading a wide variety of organic pollutants, including dyes (Blánquez et al. 2002; Casas et al. 2009; Font et al. 2003, 2006; Marco-Urrea et al. 2006).

As the number and the complexity of emerging bioremediation applications increases, there is a growing need to evaluate the environmental impact of these applications compared to conventional treatments. Determination of the best available techniques under the European IPPC Directive (European Parliament and Council of the European Union 2008a) requires the selection of the most effective techniques in achieving a high level of protection of the environment as a whole. Moreover, the Waste Framework Directive (European Parliament and Council of the European Union 2008b) encourages the integration of eco-design into the development of products and processes. In this regard, life cycle assessment (LCA) methodology (International Organisation for Standardisation—ISO 2006) is a suitable tool to analyse new technologies due to its comprehensive view and international standardisation.

In the field of industrial wastewater treatment, the LCA methodology has mainly been used to evaluate technologies based on physicochemical processes at the industrial scale (Bayer et al. 2005; Rivela et al. 2004; Romero-Hernández 2004) and to make comparisons between conventional processes and environmentally optimised alternatives (Farré et

al. 2007; García-Montaño et al. 2006; Jørgensen et al. 2004; Muñoz et al. 2006a, b, 2007; Rajakumari and Kanmani 2008; Vlasopoulos et al. 2006). In regard to the use of LCA in the field of textile wastewater, García-Montaño (2006) evaluated different decolourisation approaches based on the photo-Fenton reaction, including an oxidative process as pre-treatment for a conventional activated sludge process. Rajakumari and Kanmani (2008) assessed textile wastewater treatment using reverse osmosis filtration as the main process and combined a biological fluidised bed reactor and different physicochemical units as pre-treatments.

The present study focuses on application of the LCA methodology as a tool to evaluate biological treatment processes as they are being developed. This study uses a commercial mixture of metal-complex dyes, such as Grey Lanaset G (Ciba), as the model substrate subjected to biotransformation. Grey Lanaset G contains chromium III (2.5%) and cobalt (0.79%) as organo-metal complexes. Previous research has elucidated the biodegradation process of this dye by means of the fungus *Trametes versicolor* (Blánquez et al. 2004). Furthermore, research has demonstrated that neither the dye nor the treated effluent from this process are toxic, and the biological treatment at the pilot scale showed good efficiency (Blánquez 2005; Blánquez et al. 2007, 2008; Borràs et al. 2008; Romero et al. 2006). Moreover, the ability of the biomass removed from this system to be composted with the organic fraction of municipal waste and sewage sludge from urban wastewater has been assessed. High degrees of decomposition have been achieved, a result that guarantees the non-viability of the fungus in the finished compost. This method also ensures that total chromium content in the compost is below the maximum total concentration established by compost regulations (Blánquez 2005; Marco-Urrea 2003). However, to understand the risks of bioavailability, mobilisation and behaviour of metals in the environment, the chemical form of the metal must be known (Laborda et al. 2007). The chromium present in the residual biomass from this process is all in the form of chromium III, which has very low solubility at neutral pH and is nontoxic at low doses; in fact it is a micronutrient (Laborda et al. 2007; Puzon et al. 2008).

2 Application of the LCA methodology

According to the ISO 14040 standards (ISO 2006) the LCA includes a definition of the goal and scope, inventory analysis, impact assessment and interpretation. The three first parts are described in this section, and the interpretation is developed in Section 3.

2.1 Goal and scope

The goal of this study is to compare the environmental impact of dye treatment using the white-rot fungus *T. versicolor* with that of a standard treatment employing granular activated carbon (GAC). This work also collects life cycle inventory data, which may be relevant when studying bioremediation techniques involving white-rot fungi.

2.1.1 Functional unit

To ensure the validity of the comparison, the functional unit of the study was defined as the removal of 90% of the colour from 1 m^3 of simulated effluent with 150 mg/l of the dye Grey Lanaset G.

2.1.2 Data quality

To apply the LCA methodology, data previously obtained from laboratory and pilot experiments with bituminous coal-based activated carbon and *T. versicolor* were used (Blánquez 2005). The cellular residence time of the continuous biotechnological treatment was 21 days (Borràs et al. 2008), and the empty bed contact time of the GAC adsorption system was 21 min (Blánquez 2005). Although the primary data used in this study were taken from the experiments mentioned above, the life cycle data were scaled up to the industrial level,
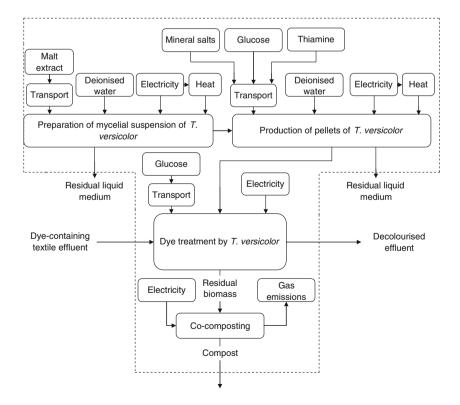
adapting them to local conditions under the following assumptions:

- The treatment plant is maintained on site by a textile company located in Sabadell (Catalonia).
- The plant operates continuously every day and has a treatment capacity of 0.43 m^3/day.
- The electricity needed for the operation of the plant comes from the Spanish grid at medium voltage.

The flow diagrams and the hypotheses made specifically to study each system are explained in Sections 2.1.3 and 2.1.4. The construction and dismantling stages of the systems were excluded under the assumption that the impacts resulting from the operational phase are much higher (Jørgensen et al. 2004; Muñoz et al. 2007).

2.1.3 Decolourisation treatment using the fungus *T. versicolor*

Figure 1 shows the flow diagram and the boundaries considered when evaluating the *T. versicolor* treatment system. This system involves five main processes: (a) growth of the fungus in the form of mycelial suspension; (b) production of the fungus in the form of pellets; (b) decolourisation of the effluent; (c) co-composting of the residual biomass and (d) transport of the nutrients required to sustain the fungus. The wastewater flows containing the residual liquid medium from the mycelial

Fig. 1 Flow diagram and system boundaries for the biological treatment system

suspension and the bioreactor used for pellet production lie within the discharge limits and were not included in the analysis.

In order to prepare the life cycle inventory data to analyse the biological system, the following were assumed:

- The development of the fungus in the form of mycelial suspension and in the form of pellets as well as the treatment stage is carried out in the same facility.
- Ingredients used in all the processes are purchased from industrial producers located in Catalonia. They are delivered by vans with a 3.5-ton maximum authorised load that travel an average of 50 km and return empty (see Section 2.2.2).
- The co-composting process is also carried out on site by means of a small composter. The wet weight of the biomass removed from the bioreactor represents 20 times the dry weight (Blánquez 2005).
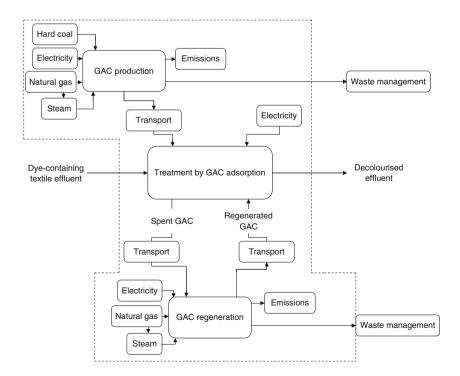
2.1.4 Decolourisation treatment using granular activated carbon

Figure 2 shows the flow diagram and the boundaries defined to analyse the GAC adsorption system. This system consists of the following processes: (a) decolourisation of the effluent; (b) off-site reactivation of the spent GAC; (c) fresh GAC production to replace the carbon that is lost during reactivation and (d) transport operations between the treatment plant and the GAC regeneration/production plant.

To complete the life cycle inventory data for the GAC system, the following assumptions were made:

- The exhausted carbon is removed from the adsorption column as slurry. The GAC with the adsorbed dye contains 50 wt.% moisture.
- The spent activated carbon is thermally regenerated in a specialised plant located in central Europe. The distance between the textile company and the regeneration plant is 1,295 km. The transport is organised through a network of less-than-truckload carriers: first, the filter is collected with a 3.5- to 7.5-ton truck at a local terminal located 100 km from the factory. It is then sent to the final destination by large trucks with an average maximum authorised mass of 16 to 32 tons (see Section 2.2.2).
- During the regeneration process, the dye is decomposed and eliminated along with 10 wt.% of the activated carbon (Bayer et al. 2005; Marsh and Rodríguez-Reinoso 2006; Muñoz et al. 2007; Romero-Hernández 2004). To properly handle the furnace off-gases, they are passed through a post-burner, a wet scrubber and a baghouse filter. The chromium and cobalt contained in the dye are retained in the solid residue from the gasification process, which is then disposed of in a residual material landfill.
- The carbon lost during the reactivation stage is replaced with fresh carbon from the same supplier. When the exhausted carbon is removed from the wastewater treatment plant, the same amount of dry carbon (regenerated and fresh) is provided.

Fig. 2 Flow diagram and system boundaries for the granulated activated carbon (GAC) system

2.2 Inventory analysis

This section describes the data collected and the sources used to prepare the inventories. To determine the inventory flows of the biological treatment system, the experimental data obtained by Borràs et al. (2008) were used. For the GAC system, the inventory flows were quantified from the experimental work carried out by Blánquez (2005). For both systems, the LCA modelling was carried out by Simapro 7.2.2 software (Pré Consultants 2010), using the Ecoinvent database v2.1 (Swiss Centre for Life Cycle Inventories, SCLCI 2010) to obtain the background data. Table 1 shows a summary of the different sources employed, which are further explained for each system in subsections 2.2.1 and 2.2.2.

2.2.1 Biological treatment

In the biological system, energy is consumed in the form of electricity. At the mycelial suspension preparation stage, electricity is used to provide agitation, to homogenise the suspension and to generate the heat required for the inoculum sterilisation. During the pellet production phase, electricity is used to operate the aeration system of the bioreactor for agitation and to supply the heat for sterilisation of the medium and the bioreactor. During the dye treatment, electricity is used to pump wastewater to the bioreactor and to operate the aeration equipment. All of these flows, derived from Borràs et al. (2008), were modelled as inputs of electricity coming from the Spanish grid (Dones et al. 2007).

Practically all of the ingredients consumed in the experiments (Borràs et al. 2008) were considered, as this is the first approach using LCA for the biological treatment system. Sodium hydroxide consumption for pH adjustment, however, was not included, assuming it is negligible. Due to the lack of availability of data from local/regional producers, production profiles were obtained from the Ecoinvent database. For ingredients not inventoried, bibliographical sources were consulted to determine the main flows involved in their production, and then the closest datasets found in the database were used.

To estimate the environmental burden of glucose, the module for maize starch manufacture modelled from data collected in Germany (Nemecek and Kägi 2007) was employed. The process for maize was taken into consideration because starch factories located in Spain process this raw material (LMC International Ltd. 2002). The energy requirements reported by Gerngross (1999) for the production of glucose are comparable to the figures used in this module, which include thermal drying of the starch as the latter stage of the process. For the manufacture of sweeteners, the starch is not dried, but it is further processed through the saccharification or starch conversion phase where it is treated with acids, enzymes or a combination of both. The resulting product is then refined and concentrated by evaporation. As a first approach to estimate the environmental impact at the crop production stage, the data included in this module were used, although there may be significant differences in cultivation or management practices at the local/regional scale.

Thiamine (vitamin B1) is also a commercialised product derived from glucose, sucrose or starch by fermentation or enzymatic conversion (Patel et al. 2006). As an approximation, the load associated with maize starch was considered (Nemecek and Kägi 2007).

An estimate of the material and energy requirements needed to produce malt extract was made from data provided by Euromalt (2010). According to this organisation, the average input required for the production of 1 ton of malt is 1.27 tons of barley, 1.18 MWh of energy and 5 m^3 of water. The final stages of malt extract production (cracking the grain, extracting the soluble fraction of malted barley and drying) were not included due to a lack of data. Because a more detailed description of the energy consumption is not given, it was assumed that all of the reported energy is thermal energy coming from the combustion of natural gas, taking into account that kilning consumes most of the energy used in malting (Kløverpris et al. 2009). The environmental burdens of these inputs were obtained from the Ecoinvent database under the assumption that the production is in Spain using the module for the conventional production of barley available for this country (Nemecek and Kägi 2007). For the allocation of the environmental impacts between malt and the by-products from its production (barley sharps and malt sprouts, which are used as forage), it was assumed that the total amount of by-products per ton of malt is 56 kg (Kløverpris et al. 2009), and their impact was deducted.

The micronutrient aluminium was understood to be supplied in the form of $Al_2(SO4)_3$ (Althaus et al. 2007), assuming that this form would work similarly to $AlK(SO_4) \cdot 12H_2O$, the compound used in the experiments. It was assumed that nitrilotriacetic acid (NTA) is added in the form of the monohydrate trisodium salt (NaNTA). The material and energy balance for its production were derived from Moarse (1994).

To account for KH_2PO_4, $CuSO_4$, $MnSO_4$, $CoSO_4$ and Na_2MoO_4, the modules from the Ecoinvent database more similar to the raw materials used for their production were selected as a first estimation. Concerning ingredient transportation, to take into account the return trip of the empty vans, the distance was doubled. To model the flows of the co-composting stage, the energy requirements and gaseous emissions reported by Martínez-Blanco et al. (2010) for home composting of biowaste and green waste were used.

Table 1 Data collection and data sources used in the life cycle inventories

Process included in the LCA Ecoinvent unit process/flow[a]	Sources
Mycelial suspension preparation, pellets production and dye treatment	Energy and ingredients consumption from experimental measurements (Borràs et al. 2008)
Sterilisation, homogenisation, agitation, aeration, pumping	
Electricity[a], medium voltage, Spanish grid	Dones et al. (2007)
Malt extract	Material and energy balance for malt production from Euromalt (2010) and Kløverpris et al. (2009)
Barley grains[a], conventional, Spain	Nemecek and Kägi (2007)
Natural gas combustion[a]	Dones et al. (2007)
Tap water[a]	Althaus et al. (2007)
Glucose	
Maize starch[a]	Nemecek and Kägi (2007)
NH_4Cl	
NH_4Cl[a]	Sutter (2007)
$ZnSO_4 \cdot 7H_2O$	
$ZnSO_4 \cdot H_2O$[a]	Hishier et al. (2007)
$MgSO_4 \cdot 7H_2O$, $CaCl_2$, $CaCl_2 \cdot 2H_2O$, NaCl, $FeSO_4 \cdot 7H_2O$, H_3BO_3, distilled water	
$MgSO_4$[a], $CaCl_2$, NaCl, $FeSO_4$, H_3BO_3, deionised water	Althaus et al. (2007)
KH_2PO_4	Stoichiometric calculations
H_3PO_4[a], 85% in water	Althaus et al. (2007)
KOH[a]	Jungbluth et al. (2007)
Nitrilotriacetic acid (NTA)	Material and energy balance for NaNTA production from Moarse (1994)
Formaldehyde[a], hydrogen cyanide, NaOH; heat, from unknown source; water	Althaus et al. (2007)
Electricity[a], medium voltage, production UCTE	Dones et al. (2007)
$MnSO_4$	Stoichiometric calculations
H_2SO_4[a]	Althaus et al. (2007)
Manganese[a], at regional storage	Classen et al. (2009)
$CoSO_4$	Stoichiometric calculations
H_2SO_4[a]	Althaus et al. (2007)
Cobalt[a], at plant	Classen et al. (2009)
$CuSO_4$	Stoichiometric calculations
H_2SO_4[a], $CuCO_3$	Althaus et al. (2007)
$AlK(SO4) \cdot 12H2O$	Stoichiometric calculations for $Al_2(SO_4)_3$
$Al_2(SO_4)_3$[a]	Althaus et al. (2007)
Na_2MoO_4	Stoichiometric calculations
Molybdenite[a]	Classen et al. (2009)
NaOH[a]	Althaus et al. (2007)
Residual biomass composting	Residual biomass from experimental measurements (Borràs et al. 2008). Electricity and gaseous emissions from Martínez-Blanco et al. (2010)
Electricity[a], low voltage, Spanish grid	Dones et al. (2007)
Emissions of CH_4[a], COV, N_2O, NH_3	Ecoinvent database v2.1 (SCLCI 2010)
Ingredients transportation	
Van[a]<3.5 t	Spielmann et al. (2007)
Continuous dye treatment with GAC	GAC requirements from experimental measurements (Blánquez 2005)
Effluent pumping to the GAC column	Experimental measurements (Blánquez 2005)
Electricity[a], medium voltage, Spanish grid	Dones et al. (2007)
GAC production	Bayer et al. (2005) and Muñoz et al. (2007)

Table 1 (continued)

Process included in the LCA Ecoinvent unit process/flow[a]	Sources
Hard coal mix[a], UCTE; hard coal combustion; electricity, medium voltage, production UCTE; natural gas combustion	Dones et al. (2007)
Deionised water[a]	Althaus et al. (2007)
GAC regeneration	Hutchins (1975) and Muñoz et al. (2007).
Hard coal combustion[a]; natural gas combustion; electricity, medium voltage, production UCTE	Dones et al. (2007)
Steam[a]	Zah and Hischier (2007)
GAC transportation	
Transport[a], lorry 3.5–7.5 t; transport, lorry 16–32 t	Spielmann et al. (2007)

[a] Life cycle datasets from Ecoinvent

2.2.2 Activated carbon process

With regard to the GAC system, activated carbon and the electricity required to operate the adsorption equipment were derived from the design and operational conditions experimentally determined and scaled up by Blánquez (2005). Requirements of activated carbon would change if a different kind of activated carbon than that used in this study was used.

The material and energy balance from Bayer et al. (2005) were used for the fresh GAC manufacture. We employed the Ecoinvent module for hard coal consumed in UCTE power plants (Dones et al. 2007) to estimate the environmental load of bituminous coal due to the lack of data on the chain of the coal up to the thermal activation plant (Muñoz et al. 2007). To estimate the environmental load of the process of GAC regeneration, following Muñoz et al. (2007), data from Hutchins (1975) on thermal regeneration in a multiple hearth furnace were used.

The assumed distance of 1,295 km between the textile company and the regeneration/activation plant is the one from the textile company to the plant managed by the provider of the GAC, which admits small volumes of activated carbon and small returnable equipment for treatment. It also corresponds to the average distance between the textile company and the regeneration plants belonging to ACPA located in central Europe (Cefic 2010).

2.3 Impact assessment

Only the phases of the life cycle impact assessment (LCIA) required by the ISO 14040 standard (ISO 2006) were conducted. These phases are the selection of impacts and the LCIA methods, the assignment of inventory results to impact categories (classification) and the calculation of category indicator results (characterisation).

The impact categories studied were climate change (CC), ozone depletion (OD), human toxicity (HT), photochemical oxidant formation (POF), terrestial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TEco), freshwater ecotoxicity (FEco), marine ecotoxicity (MEco), metal depletion (MD) and fossil depletion (FD). The midpoint characterisation methods selected are those defined by ReCiPe (Goedkoop et al. 2008). The cumulative energy demand (CED) flow indicator, proposed by Ecoinvent (Hischier et al. 2009), was also included in the analysis.

Although from the regulatory point of view, neither Grey Lanaset G nor wastewaters containing it are toxic, human toxicity and ecotoxicity impacts have been included in this study because the ingredients and the energy used in the biological process (and the same for the flows involved in the GAC adsorption system) might imply the use of substances considered toxic as defined by LCI characterisation methods.

3 Results and discussion

In this section, the inventory and the life cycle impact assessment results are presented followed by a sensitivity analysis of the results.

3.1 Inventory results

Tables 2 and 3 summarise the inventory results for the two systems evaluated. As indicated in Table 2, 139 g of the fungus *T. versicolor* are required per functional unit; this requires the preparation of 143 ml of mycelial suspension and produces 87 g of residual biomass (1.73 kg wet weight).

Sterilisation of culturing vessels and media accounts for 58% of the total electricity used per functional unit, followed by aeration, which accounts for 25%. The most energy-intensive stage is the preparation of the mycelial suspension, where autoclaving requires 39% of the total electricity used.

Glucose is the carbon source used for the growth of *T. versicolor* in pellet form and for its maintenance during the

Table 2 Life cycle inventory for the biological treatment system

Process	Amount	Units
Mycelial suspension preparation (0.143 l)		
Sterilisation	10.2	kWh
Homogenisation and agitation	1.10	kWh
Malt extract	8.57	g
Deionised water	0.428	kg
Pellets production (139 g dry weight)		
Sterilisation	4.96	kWh
Agitation	0.38	kWh
Aeration	4.02	kWh
Glucose	250	g
NH_4Cl	75.0	g
KH_2PO_4	71.4	g
$MgSO_4$	18.9	g
$CaCl_2$	3.61	g
NaNTA	536	mg
$MnSO_4$	179	mg
NaCl	357	mg
$FeSO_4$	35.7	mg
$CoSO_4$	35.7	mg
ZnSO4	35.7	mg
$CuSO_4$	3.57	mg
$Al_2(SO_4)_3$	5.15	mg
H_3BO_3	3.57	mg
Na_2MoO_4	3.57	mg
Deionised water	35.7	kg
Start-up treatment medium		
Glucose	167	g
NH_4Cl	39.6	g
KH_2PO_4	4.17	g
$MgSO_4$	1.10	g
$CaCl_2$	210	mg
NaNTA	31.3	mg
$MnSO_4$	10.4	mg
NaCl	20.8	mg
$FeSO_4$	2.08	mg
$CoSO_4$	2.08	mg
$ZnSO_4$	2.08	mg
$CuSO_4$	208	µg
$Al_2(SO_4)_3$	301	µg
H_3BO_3	208	µg
Na_2MoO_4	208	µg
Deionised water	20.8	kg
Continuous dye treatment		
Pumping	2.79	kWh
Aeration	2.65	kWh
Glucose	775	g
Co-composting of residual biomass (1.73 kg wet weight)		
Electricity, low voltage, Spanish grid	0.0163	kWh
Emissions of CH_4	274	mg

Table 2 (continued)

Process	Amount	Units
Emissions of COV	970	mg
Emissions of N_2O	1.17	g
Emissions of NH_3	1.46	g
Ingredients transportation		
Transport, van<3.5 t	0.143	tkm

Values are reported per functional unit

dye treatment phase. At the treatment stage, glucose represents 67% (w/w) of the total consumption of ingredients needed per functional unit, and total glucose supply adds up to nearly 85% of the total consumption of ingredients.

Concerning the GAC system, as shown in Table 3, 10 kg of GAC are required per functional unit, of which 9 kg are regenerated and 1 kg is oxidised during the reactivation process. Therefore, this 1 kg of GAC must be replaced by fresh activated carbon. The major input to the regeneration process is the natural gas required to generate steam. As for fresh GAC production, hard coal and natural gas are the main inputs.

3.2 Environmental assessment results

Figure 3 shows the relative impact contributions of the systems in the categories analysed. The impact values have
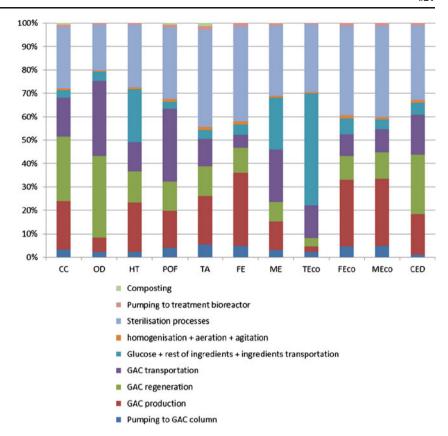
Table 3 Life cycle inventory for the GAC system

Process	Amount	Units
Continuous dye treatment (10 kg dry weight GAC)		
Pumping	2.79	kWh
GAC production (1 kg GAC)		
Hard coal	1.00	kg
Hard coal combustion	60.8	MJ
Electricity, medium voltage, production UCTE	1.60	kWh
Deionised water	12.0	kg
Natural gas combustion	13.2	MJ
GAC regeneration (10 kg to regenerate, 9 kg produced)		
Electricity, medium voltage, production UCTE	0.30	kWh
Hard coal combustion	30.4	MJ
Steam	6.00	kg
Natural gas combustion	105	MJ
GAC transport (regenerated and fresh) to the textile company (10 kg)		
Transport, lorry 3.5–7.5 t, EURO4	1.00	tkm
Transport, lorry 16–32 t, EURO4	11.95	tkm
Spent GAC transport to the regeneration plant (20.3 kg wet weight)		
Transport, lorry 3.5–7.5 t, EURO4	2.03	tkm
Transport, lorry 16–32 t, EURO4	24.22	tkm

Values are reported per functional unit

Fig. 3 Life cycle impact assessment results for the treatment systems under study. The GAC system is represented in grey colours, whereas the biological treatment is shown in patterns. The acronyms used are as follows: climate change (*CC*), ozone depletion (*OD*), human toxicity (*HT*), photochemical oxidant formation (*POF*), terrestial acidification (*TA*), freshwater eutrophication (*FE*), marine eutrophication (*ME*), terrestrial ecotoxicity (*TEco*), freshwater ecotoxicity (*FEco*), marine ecotoxicity (*MEco*), metal depletion (*MD*), fossil depletion (*FD*) and cumulative energy demand (*CED*)

been distributed among the main processes included in each system (see Electronic Supplementary Material for detailed values).

In the biological treatment system, the electricity used to sterilise the media for the formation of the mycelia suspension and pellets represents the highest contribution in nearly all categories, with values between 18% in OD category to 40% in FE and TA categories. The main contribution is due to the sterilisation of the media for mycelia formation, the contributions of sterilisation during pellet production ranges from 4% to 15% of the total impact scores. Aeration of the bioreactor, homogenization and pumping of the effluent represent between 3% and 6% of the total impacts. Globally, electricity consumption accounts for between 37% and 97% of the total. Usually the energy consumption of large-scale processes is lower than the consumption of laboratory or pilot-scale processes due to the increase in the efficiency of industrial systems. The maintenance of steady state during long-time operation also contributes to decreasing the energy consumption of large-scale processes.

Total glucose supply plus rest of ingredients and transport represents the largest contribution in TEco category, accounting for 61% of the total impact attributable to the biological system. This contribution is due mainly to glucose, because of the cereal production stage, which represents more than 95% of the total impact assigned to glucose. The contribution of this nutrient in the remaining categories does not exceed 20%. Consequently, it is worth considering whether

a given biological resource that is suitable for a technological application has been produced under environmentally sound conditions or whether lower grade biomass resources would also serve as a carbon source for the fungus. The rest of the ingredients show minor contributions, with values ranging from 2% to 8% (in TEco).

The transport of the ingredients shows a low contribution in all categories (1–4%), as well as the rest of ingredients (2–8%). Similarly, composting presents a reduced contribution in all categories (0–3%).

In the GAC system, activated carbon production and regeneration are the main contributors to the impact values. Altogether, they account for between 42% and 75% of the total impact. The contribution of the GAC transportation is also notable, especially in POF, OD and ME where it accounts for 30%, 33% and 22% of the total impact, respectively.

Comparison of the two systems reveals that the biological treatment system has the lowest environmental impact in six categories. The biological treatment represents 37% of the GAC score in OD, almost half the impact of the GAC system in POF and CC, and 70% of the GAC score in CED; furthermore, in MEco, its impact is 4% lower than that of the GAC system (see Section 3.3).

Although knowing that when a global textile system is analysed the results of wastewater treatment in relation to the whole system are less than 1% (data not shown) in eutrophication and cumulative energy demand, it is important

to identify causes of environmental impacts and reduce such impacts while avoiding shifting of environmental burdens.

3.3 Sensitivity analysis

The LCIA results for the biological treatment system indicate that electricity requirements, especially for electrical sterilisation, are key drivers for practically all of the impact categories. However, instead of using an electric heating system, steam for sterilisation may be directly generated by means of a steam generator that can be easily integrated in a textile industry. The textile finishing industry is known for high heat demand in many of its processes, and steam generators are one of the energy-efficient technologies implemented by this sector in Catalonia (Leitat Technological Center 2006). Cogeneration is another energy-efficient technology with a significant degree of implementation. In this study, only the former alternative has been applied, assuming that heat requirements for sterilisation are provided by natural gas (TV_gas) and a mixture of hard coal, light fuel oil and natural gas (TV_mix). The results are displayed in Table 4. In the last four columns, these results are compared with the results obtained in the initial scenario (TVI) and with those corresponding to the GAC system, assigning a relative score of 100% to the option with the worst performance in each impact category.

According to the results from Table 4, there is a significant improvement compared to the initial scenario in terms of TA for both new scenarios and of FE for TV_gas scenario. Directly generating steam allows the biological treatment system to obtain a better assessment than the GAC system in all categories with the exception of ME and TEco. The

influence of the origin of the fuel is also evident because natural gas is a cleaner alternative.

However, one of the main factors that create more uncertainty is scale up from the pilot plant to the industrial one. It had been assumed that the energy consumption of large-scale processes would be lower than the consumption of laboratory or pilot-scale processes due to the increase in the efficiency of industrial systems. Therefore it has been studied that there would be impacts if there was a decrease in electricity consumption 10%. Results (see Electronic Supplementary Material) show that this improvement may not significantly affect the impacts. Therefore, the most significant improvements will come through changes in technology and pellet production rather than by scaling.

The main objective of this work was not to optimise the GAC system but to use it as a reference process. It is therefore important for future studies to analyse the influence of GAC process improvement, for example, using a more effective GAC. With an appropriate GAC, the total amount of GAC used in the process would be 10% lower, which would result in a 10% maximum decrease in the impact categories.

4 Conclusions

The LCA shows that the biological treatment process using the fungus *T. versicolor* to remove Grey Lanaset G offers environmental advantages in four impact categories (CC, OD, POF and CED) in comparison with the traditional GAC adsorption method, and at least in four categories (HT, TA, FE and FEco) the difference between the

Table 4 Sensitivity analysis of LCIA results when steam is directly generated on site

Impact category	Unit	GAC	TVI	TV_gas	TV_mix	GAC (% of highest)	TVI (% of highest)	TV_gas (% of highest)	TV_mix (% of highest)
CC	kg CO2 eq	3.26E+01	1.75E+01	1.49E+01	1.59E+01	100	54	46	49
OD	kg CFC-11 eq	2.72E−06	1.01E−06	1.06E−06	1.09E−06	100	37	39	40
HT	kg 1.4-DB eq	7.81E−01	8.63E−01	7.47E−01	7.86E−01	90	100	87	91
POF	kg NMVOC	9.31E−02	6.19E−02	4.51E−02	4.78E−02	100	66	48	51
TA	kg SO2 eq	1.12E−01	1.26E−01	8.97E−02	9.53E−02	89	100	71	75
FE	kg P eq	6.66E−03	6.97E−03	5.00E−03	5.24E−03	96	100	72	100
ME	kg N eq	3.00E−02	3.83E−02	3.22E−02	3.31E−02	78	100	84	86
TEco	kg 1.4-DB eq	2.17E−03	7.87E−03	7.24E−03	7.54E−03	28	100	92	96
FEco	kg 1.4-DB eq	1.11E−01	1.14E−01	8.33E−02	8.74E−02	97	100	73	76
MEco	kg 1.4-DB eq	9.16E−02	8.75E−02	6.23E−02	6.63E−02	100	96	68	72
MD	kg Fe eq	4.53E−01	3.47E−01	2.95E−01	3.00E−01	100	77	65	66
FD	kg oil eq	1.02E+01	4.60E+00	4.16E+00	4.36E+00	100	45	41	43

The initial scenario for the biological system when applying electrical heating (TVI), the scenario when steam is generated from the combustion of natural gas (TV_gas) and the scenario when steam is generated from the combustion of a mixture of fossil fuels (TV_mix) are shown. A relative score of 100% is assigned to the option with the worst performance in each impact category, and the rest of scenarios are compared to it

contribution of the two processes are not significant enough to allow the discrimination of one of the processes.

In both systems, energy consumption is the principal contributor to the environmental impact. In the biological process, energy is used to sterilise the mycelial suspension, the medium and the bioreactor for pellet production as well as to aerate the reactors for pellet production and for wastewater treatment. The inoculum sterilisation is the most crucial determinant of environmental impact. Generating steam directly for autoclaving is effective at reducing the environmental impact. When the scenario of biological treatment with direct steam generation is compared to the GAC system, it obtains a more favourable assessment in 10 of the 12 impact categories. One possible way to reduce the terrestrial ecotoxicity impact is to utilise a low-grade carbon source or a residual carbon source as an alternative to glucose. In this way, the biological process would be better from the environmental point of view.

Overall, this study highlights important aspects in the biological process that should be addressed to continuously improve the environmental performance of this process. This study also provides environmental data and an indication of the potential impacts of characteristic processes that may be of interest for other applications in the field of biological waste treatment and wastewater treatment involving white-rot fungi.

References

Althaus HJ, Chudacoff M, Hischier R, Jungbluth N, Osses M, Primas A (2007) Life cycle inventories of chemicals. Ecoinvent report No. 8, v2.0. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Bayer P, Heuerb E, Karlb U, Finkela M (2005) Economical and ecological comparison of granular activated carbon (GAC) adsorber refill strategies. Water Res 39(9):1719–1728

Blánquez P (2005) Development of a pilot scale process for the treatment of the Grey Lanaset G textile dye by *Trametes versicolor* (in Catalan). PhD. Department of Chemical Engineering, Universitat Autònoma de Barcelona, Catalonia, Spain. ISBN: 84-689-22-88-9

Blánquez P, Caminal G, Sarrà M, Vicent T, Gabarrell X (2002) Olive oil mill waste waters decoloration and detoxification in a bioreactor by the white rot fungus *Phanerochaete flavido-alba*. Biotechnol Progr 18(3):660–662

Blánquez P, Casas N, Font X, Gabarrell X, Sarrà M, Caminal G, Vicent T (2004) Mechanism of textile metal dye biotransformation by *Trametes versicolor*. Water Res 38(8):2166–2172

Blánquez P, Caminal G, Sarrà M, Vicent T (2007) The effect of HRT on the decolourisation of the Grey Lanaset G textile dye by *Trametes versicolor*. Chem Eng J 126(2–3): 163–169

Blánquez P, Sarrà M, Vicent T (2008) Development of a continuous process to adapt the textile wastewater treatment by fungi to industrial conditions. Biochemistry 43(1):1–7

Borràs E, Blánquez P, Sarrà M, Caminal G, Vicent T (2008) *Trametes versicolor* pellets production: low-cost medium and scale-up. Biochem Eng J 42(1):61–66

Casas N, Parella T, Vicent T, Caminal G, Sarrà M (2009) Metabolites from the biodegradation of triphenylmethane dyes by *Trametes versicolor* or laccase. Chemosphere 75(10):1344–1349

Cefic (European Chemical Industry Council) (2010) Activated Carbon Producers Association (ACPA). www.cefic.be. Accessed March 2010

Classen M, Althaus HJ, Blaser S, Tuchschmid M, Jungbluth N Doka G, Faist Emmenegger M, Scharnhorst W (2009) Life cycle inventories of metals. Final report Ecoinvent data v2.1, No. 10. EMPA Dübendorf, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Dones R, Bauer C, Bolliger R, Burger B, Faist Emmenegger M, Frieschknecht R, Heck T, Jungbluth N, Röder A, Tuchschmid M (2007) Life cycle inventories of energy systems: results for current systems in Switzerland and other UCTE countries. Ecoinvent report No. 5. Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Euromalt (2010) Facts on EU malting. Brussels, www.coceral.com/cms/beitrag/10012002/238410. Accessed March 2010

European Parliament and Council of the European Union (2008a) Directive 2008/1/EC of the European Parliament and the Council of 15 January 2008 concerning integrated pollution prevention and control. Official Journal of the European Union L24/8, 29.1.2008

European Parliament and Council of the European Union (2008b) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Official Journal of the European Union L 312/3, 22.11.2008

Farré MJ, García-Montaño J, Ruiz N, Muñoz I, Domènech X, Peral J (2007) Life cycle assessment of the removal of Diuron and Linuron herbicides from water using three environmentally friendly technologies. Environ Technol 28 (7):819–830

Font X, Caminal G, Gabarrell X, Romero S, Vicent T (2003) Black liquor detoxification by laccase of *Trametes versicolor* pellets. J Chem Technol Biotechnol 78(5):548–554

Font X, Caminal G, Gabarrell X, Vicent T (2006) Treatment of toxic industrial wastewater in fluidized and fixed-bed batch reactors with *Trametes versicolor*: influence of immobilisation. Environ Technol 27(8):845–854

García-Montaño J, Ruiz N, Muñoz I, Domènech X, García-Hortal JA, Torrades F, Peral J (2006) Environmental assessment of different photo-Fenton approaches for commercial reactive dye removal. J Hazard Mater 138(2):218–225

Gerngross TU (1999) Can biotechnology move us toward a sustainable energy? Nat Biotechnol 17:541–544

Goedkoop MJ, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R, ReCiPe (2008) A life cycle impact assessment method which comprises harmonised cathegory indicators at the midpoint level; First edition Report I: characterization;6 January 2009, http://www.lcia-recipe.net

Hischier R, Classen M, Lehmann M, Scharnhorst W (2007) Life cycle inventories of electric and electronic equipment: production, use and disposal. Ecoinvent report No. 18. EMPA/Technology-

Society Lab, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Hischier R, Weidema B, Althaus HJ, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, Köllner T, Loerincik Y, Margni M, Nemecek T (2009) Implementation of Life cycle impact assessment methods. Ecoinvent report No. 3, v2.1. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Hutchins RA (1975) Thermal regeneration costs. Chem Eng Prog 71 (5):80–86

ISO (2006) ISO 14044: environmental management–life cycle assessment–requirements and guidelines. Switzerland, Geneva

Jørgensen KR, Villanueva A, Wenzel H (2004) Use of life cycle assessment as decision-support tool for water reuse and handling of residues at a Danish industrial laundry. Waste Manage Res 22 (5):334–345

Jungbluth N, Chudacoff M, Dauriat A, Dinkel F, Doka G, Faist Emmenegger M, Gnansounou E, Kljun N, Schleiss K, Spielmann M, Stettler C, Sutter J (2007). Life cycle inventories for bioenergy. Ecoinvent report No. 17. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Kløverpris JH, Elvig N, Nielsen PH, Nielsen AM, Ratzel O, Karl A (2009) Comparative life cycle assessment of malt-based beer and 100% barley beer. Novozymes. www.novozymes.com

Laborda F, Górriza MP, Bolea E, Castillo JR (2007) Mobilization and speciation of chromium in compost: a methodological approach. Sci Total Environ 373(1):383–390

Leitat Technological Center (2006) Study of energy efficiency in the textile finishing sector and situation in Catalonia (in Catalan). Report prepared for the Institut Català d'Energia. Institut Català d'Energia, Catalonia, Spain

LMC International Ltd (2002) Evaluation of the community policy for starch and starch products. Report prepared for the European Commission, DG Agriculture. LMC International Ltd, Oxford, New York, p 20

Marco-Urrea E (2003) Preliminary study to conduct a risk analysis on the release of Trametes versicolor into the soil: experimental study (in Catalan). Master's Thesis, Department of Chemical Engineering, Universitat Autònoma de Barcelona, Catalonia, Spain

Marco-Urrea E, Gabarrell X, Sarrà M, Caminal G, Vicent T, Reddy CA (2006) Novel aerobic perchloroethylene degradation by the white-rot fungus Trametes versicolor. Environ Sci Technol 40 (24):7796–7802

Marsh H, Rodríguez-Reinoso F (2006) Activated carbon. Elsevier Ltd, The Netherlands, UK, USA, pp 428–463

Martínez-Blanco J, Colón J, Gabarrell X, Font X, Sánchez A, Artola A, Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Manage 30(6):983–994

Moarse GK, Lester JN, Perry R (1994) The environmental and economic impact of key detergent builder systems in the European Union. Imperial College of Science, Technology and Medicine, University of London. Centre Européen d'Études des polyphosphates E.V., Selper Publications, London, UK, p. 53, <www.ceep-phosphates.org/Documents/shwList.asp?NID=4&HID=30>

Muñoz I, Peral J, Ayllón JA, Malato S, Passarinho P, Domènech X (2006a) Life cycle assessment of a coupled solar photocatalytic–biological process for wastewater treatment. Water Res 40 (19):3533–3540

Muñoz I, Rieradevall J, Torrades F, Peral J, Domènech X (2006b) Environmental assessment of different advanced oxidation processes applied to a bleaching Kraft mill effluent. Chemosphere 62(1):9–16

Muñoz I, Peral J, Ayllón JA, Malato S, Martin MJ, Perrot JY, Vicent M, Domènech X (2007) Life-cycle assessment of a coupled advanced oxidation-biological process for wastewater treatment: comparison with granular activated carbon adsorption. Environ Eng Sci 24(5):638–651

Nemecek T, Kägi T (2007) Life cycle inventories of Swiss and European agricultural production systems. Final report Ecoinvent v2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf, Switzerland

Patel M, Crank M, Dornburg V, Hermann BG, Roes L, Hüsing B, Overbeek L, Terragni F, Recchia E (2006) Medium and long-term opportunities and risks of the biotechnological production of bulks chemicals from renewable sources—the potential of White Biotechnology. The BREW Project. Report prepared under the European Commission's GROWTH Programme, DG Research. Utrecht University, Utrecht, The Netherlands, p 70

Poiger T, Richardson SD, Baughman GL (2000) Analysis of anionic metallized azo and formazan dyes by capillary electrophoresis–mass spectrometry. J Chromatogr A 886(1–2):259–270

PRé Consultants (2010) SimaPro 7.2.2. PRé Consultants, Amersfoort, The Netherlands

EIPPCB (European Integrated Pollution and Prevention Control Bureau) (2003) Integrated pollution prevention and control. Reference document on best available techniques for the textiles industry. European IPPC Bureau, European Commission, Seville, Spain

Puzon GJ, Tokala RK, Zhang H, Yonge D, Peyton BM, Xun L (2008) Mobility and recalcitrance of organo–chromium(III) complexes. Chemosphere 70(11):2054–2059

Rajakumari SP, Kanmani S (2008) Environmental life cycle assessment of zero liquid discharge treatment technologies for textile industries, Tirupur—a case study. J Sci Ind Res 67(6):461–467

Rivela B, Moreira MT, Bornhardt C, Méndez R, Feijoo G (2004) Life cycle assessment as a tool for the environmental improvement of the tannery industry in developing countries. Environ Sci Technol 38(6):1901–1909

Robinson T, McMullan G, Marchant R, Nigam P (2001) Remediation of dyes in textile effluent: a critical review on current treatment technologies with a proposed alternative. Bioresource Technol 77 (3):247–255

Romero S, Blánquez P, Caminal G, Font X, Sarrà M, Gabarrell X, Vicent T (2006) Different approaches to improving the textile dye degradation capacity of Trametes versicolor. Biochem Eng J 31 (1):42–47

Romero-Hernández O (2004) To treat or not to treat? Applying chemical engineering tools and a life cycle approach to assessing the level of sustainability of a clean-up technology. Green Chem 6 (8):395–400

Spielmann M, Bauer C, Dones R, Tuchschmid M (2007) Transport services. Ecoinvent report No. 14, Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland

Sutter J (2007) Life cycle inventories of highly pure chemicals. Ecoinvent report No. 19. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland.

Swiss Centre for Life Cycle Inventories (SCLCI) (2010) Ecoinvent data v2.1. Dübendorf, Switzerland

Vlasopoulos N, Memon FA, Butler D, Murphy R (2006) Life cycle assessment of wastewater treatment technologies treating petroleum process waters. Sci Total Environ 367(1):58–70

Zah R, Hischier R (2007) Life cycle inventories of detergents. Ecoinvent report No. 12. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland